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DESIGN AND FABRICATION OF WING OF A HIGH-PAYLOAD AERIAL VEHICLE

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ABSTRACT

The demand for an Unmanned Aerial Vehicle (UAV) is increasing by day by day due to its wide applications in diverse sectors, ranging from commercial applications to military and disaster relief missions. This paper deals with the design optimization and fabrication of the wing, which has a vital role in the lift generation. The design methodology involves a multidisciplinary system engineering approach towards the selection of pertinent factors. Wing design begins with the conceptual design and configuration selection, wherein the measurements of the wing are deduced. Balsa wood, Birch wood and aluminium were selected for the wing fabrication. A live I/O MATLAB script was utilized to calculate the dimensions of the web, flange, and related load-bearing members. The code also checks for the failure of the spar's web under shear buckling and optimizes the thickness of the web accordingly. For a better understanding of the behaviour of materials and their response to various loads, Finite Element Analysis was done on Ansys Static Structural software. Eventually, the fabrication of the designed wing was carried out with the aid of CNC router cut and the constituent parts were assembled.

KEY WORDS: Unmanned Aerial Vehicle, Finite Element Method, MATLAB, Low-Cost Prototyping, WING & Ansys

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Original Article

INTRODUCTION

Aerostructure [1, 2] must produce safe and reliable systems with minimal weight keeping in mind the cost-effectiveness and operational conditions of the vehicle. Many of these operating conditions are harsh as they operate in extreme environments including a wide range of temperatures, pressure, and environmental loads. The airplane was the first major technology with weight as an overriding concern where majorly, all the performance parameters are affected inversely with the change in weight. The mission and range of an aircraft affect the weight variations in the system. Along with the total weight, the weight distribution also plays a major role in the designing of the control surfaces with the impact of the range, manoeuvrability and the performance of the aircraft. Aircraft wing requires structural elements like stringers, flanges, and webs that support the distribution of weight and various loads [3].

A fixed-wing UAV is an unmanned vehicle developed for long-range high endurance missions like search and rescue, mapping, surveillance, and defense. The fixed wings are responsible for the production of lift in response to forward accelerating force. The fixed wing UAV provides more efficient aerodynamics and has longer flight duration when compared to a multirotor.

This paper focuses on the application of basic structural theory[4] and knowledge of materials to design, develop and fabricate the wing of a high endurance and high payload fixed-wing UAV. The fundamental problem solved is the identification of materials, shape and dimensions of a wing of a fixed-wing UAV used for a high payload mission. The design methodology involves a multidisciplinary system engineering approach towards the

selection of various factors and performance index. The objectives of the paper are i) deduction of the measurements of the wing, ii) material selection and computational study of their response to various loading conditions, iii) optimisation of the thickness of the web by running a live I/O MATLAB script, iv) structural analysis of wing using Finite Element Method, and finally v) the fabrication and testing of the fixed wing.

DESIGN PROCESS

Conceptual Design Procedure

A similar class of UAVs was considered RMRC Air Titan [5], RMRC Anaconda [6], Sig Rascal 110 [7] to deduce the conceptual design parameters, where in payload capacity and high endurance are given precedence during selection. To ensure the sustainability of aircraft during extreme maneuvers without fracture, the design factor and the lift load factor were chosen as 1.5 and 5g respectively. Furthermore, the initial configuration was selected single-wing after narrowing down from several available configurations. Some other parameters namely, aspect ratio, wingspan, chord length were calculated. Lastly, S1223 [8], a high lift airfoil was chosen due to its suitable characteristics.

Table 1: Wing Parameters

S. No.	Parameter	Value/Range
1.	Root chord	390 mm
2.	Tip chord	277.7 mm
3.	Empty weight	< 5 kg
4.	Lift load	5g
5.	Design factor	1.5
6.	Exposed half span	1200 mm
7.	Exposed half wing area	0.81m^2

Preliminary Design Procedure

Empirical Relations

A variety of wing structures [9-12] were studied and the following range of parameters was assumed:

- Distance between adjacent ribs: 10-12 cm. A higher distance would not only decrease the strength of the wing but also would destroy the aerodynamic shape required for the wing. At the same time, a lower distance would increase the number of ribs, adding to unnecessary weight to the structure. Further, a constant distance between the ribs allows easy calculation and fabrication.
- Position of front spar: 18-25% of the chord length. The distance between the front spar and aerodynamic centre should be minimized to prevent torsion. Similarly, it should not be kept too close to the rear spar, as it would render the function of the front spar as futile.
- Position of rear spar: 62-65% of the chord length. The rear spar not only adds to the strength but also acts as a supporting member for the aileron (control surface used for the roll of aircraft). Thus, a too far position would diminish the thickness of the spar, resulting in it to be ineffectual.
- Position of the centre of pressure: 45% of the chord length. Although the position of the centre of pressure varies with the angle of attack, this value is suitable and can be used for calculation purposes.

Material Selection

- Balsa wood – ribs, leading-edge and skin. The material has a low density and exhibits high strength characteristics. The wood fibres can be aligned along the direction of the load to bear maximum strength.
- Birchwood – rear spar and stringers. Although it has a specific gravity higher than that of Balsa wood, the yield strength is much higher and can be used in members subjected to a higher load.
- Aluminium – Front spar. The front spar experiences the maximum force and thus needed to be a metal. Aluminium, when compared to steel, has an advantage over weight, and can also sustain the load experienced by the front spar.

Detail Design and Mathematical Model

The wings bear an enormous lift force and the structure requires to be durable. At the same time, over-building the structure would add to unnecessary weight of the aircraft. Thus, an intelligent algorithm needed to be articulated that took into account various factors, affecting the design of the wing. A MATLAB live I/O script was developed which calculates the optimum dimensions of spar for the wing. The following flow chart describes the algorithm used in the code.

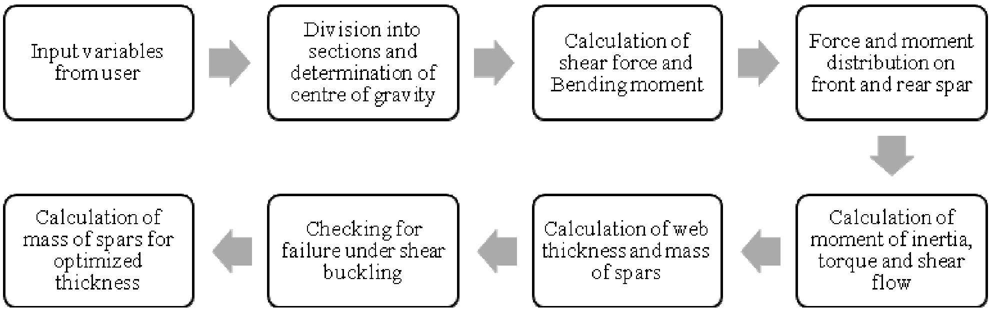


Figure 1: Algorithm for I/O MATLAB Script.

The following excerpts are included from MATLAB code:

- Parameters inputted into the code

```
prompt1='Enter the mass in kg ';
mass=input(prompt1);
prompt2='Enter the root chord in mm ';
root=input(prompt2);
```

Figure 2: MATLAB Code (i).

- Division of wing into 10 sections and calculating the centre of gravity of each trapezoid section:

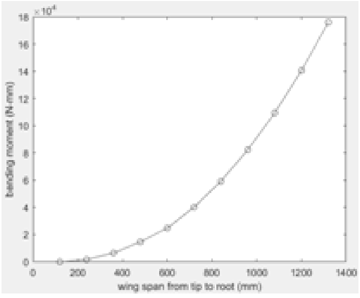
```
area=0.5*(root+tip)*span;
width_each_section=span/10; %10 sections%
h=width_each_section;
l(1)=tip;
for i=2:11
    l(i)=root-((root-l(1))/span)*(span-(h*(i-1)));
    area_tr(i)=0.5*(l(i)+l(i-1))*h;
    cg(i)=h/3*((tip+2*l(i))/(tip+l(i)));
end
```

Figure 3: MATLAB Code (ii).

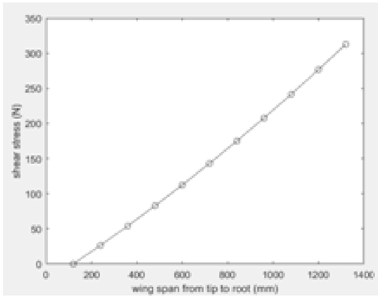
- Calculation of shear force and bending moment:

```
design_factor=1.5;
design_load=limit_load*design_factor;
design_load_half=design_load/2;
pr=design_load_half/area;

for i=2:11
    if(i==2)
        load(i)=pr*area_tr(i);
    end
    load(i)=pr*area_tr(i)+load(i-1);
end

for i=2:11
    p(i)=pr*area_tr(i);
end

bm(1)=0;
bm(2)=p(2)*cg(2);
bm(3)=p(2)*cg(2)+p(3)*cg(3)+p(2)*h;
```

(A)



(B)



(C)

Figure 4: (A) MATLAB Code (iii); (B) Variation of Shear Stress along the Span; (C) Variation of Bending Moment Along the Wingspan.

- Distribution of forces on the front and rear spar:

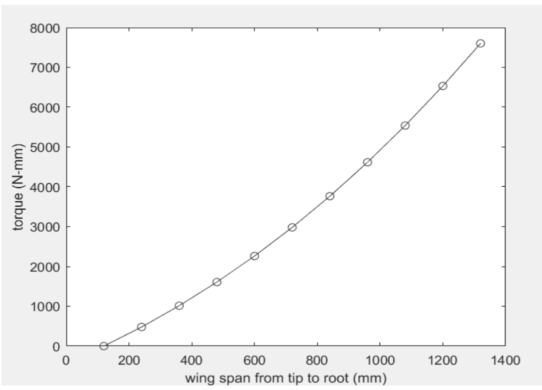
```
    %a=location of front spar from cp
%b=location of rear spar from cp
%c=a+b
for i=1:11
    poscp(i)=cp_from_le*l(i);
    posfp(i)=fs_from_le*l(i);
    posrp(i)=rs_from_le*l(i);
    a(i)=poscp(i)-posfp(i);
    b(i)=posrp(i)-poscp(i);
    c(i)=a(i)+b(i);
end

for i=1:11
    shearfs(i)=load(i)*b(i)/c(i);
    shearrs(i)=load(i)-shearfs(i);
```

Figure 5: MATLAB Code (iv).

- Moment of inertia and torque developed

```
for i=1:11
    moifs(i)=bmfs(i)*thickfs*0.5/tensile;
    moirs(i)=bmrs(i)*thickrs*0.5/tensile;
end

torque_cum(1)=0;
for i=2:11
    areabox(i)=0.5*(thickfs+thickrs)*c(i);
    cgbox(i)=c(i)/3*((thickrs+(2*thickfs))/(thickrs+thick
    distance_cg_cp(i)=cgbox(i)-b(i);
    torque(i)=load(i)*distance_cg_cp(i);
    torque_cum(i)=torque(i);
    torque_cum(i)=torque_cum(i)+torque_cum(i-1);
    g(i)=torque_cum(i)/(2*areabox(i));
end
```

(A)



(B)

Figure 6: (A) MATLAB Code (v); (B) Variation of Torque Along the Wingspan.

- Thickness of the web and mass of spars:

```
for i=1:11
    twebfs(i)=totalfs(i)/(thickfs*shear);
    areawebfs(i)=thickfs*twebfs(i);
    moiwebfs(i)=(twebfs(i)*(thickfs)^3)/12;
    twebrs(i)=totalrs(i)/(thickrs*shear);
    areawebrs(i)=thickrs*twebrs(i);
    moiwebrs(i)=(twebrs(i)*(thickrs)^3)/12;
end
```

Figure 7: MATLAB Code (vi).

- Optimization by checking for failure under shear buckling:

```
tweb1=1;
a_new=1;
for i=2:11
    a=twebfs(i);
    j=0;
    while((a~=tweb1)&&(j<100))
    a=a_new;
    fin=q(i)/a;
    tweb1=(fin*thickfs*thickfs/(K*young))^0.5;
    a_new=tweb1;
    j=j+1;
    end
    final_web_fs(i)=a;
end
```

Figure 8: MATLAB Code (vii).

- Calculation of mass of spars for optimized thickness:

```
for i=2:11
    areanewwebfs(i)=final_web_fs(i)*thickfs;
    areanewwebrs(i)=final_web_rs(i)*thickrs;
    volnewfs(i)=(areanewwebfs(i)+aflanfs(i))*h;
    volnewrs(i)=(areanewwebrs(i)+aflanrs(i))*h;
end

volnewtotal=sum(volnewfs)+sum(volnewrs);
massnew=densityfs*volnewtotal
```

Figure 9: MATLAB Code (viii).

Table 2: Comparison of Shear Web Thickness

Rib	Front Spar Web Thickness (mm)		Rear Spar Web Thickness (mm)	
	Before Optimization	After Optimization	Before Optimization	After Optimization
1	0	0	0	0
2	0.002	0.0694	0.071	0.434
3	0.0046	0.1001	0.149	0.601
4	0.0077	0.10262	0.234	0.706
5	0.0114	0.1497	0.327	0.820
6	0.0156	0.1715	0.427	1.124
7	0.0203	0.1920	0.535	1.423
8	0.0256	0.2116	0.651	1.617
9	0.0315	0.2304	0.774	1.907
10	0.0380	0.2485	0.905	2.195
11	0.0451	0.2661	1.044	2.791

Table 3: Mechanical Parameters for Front and Rear Spar

Rib	Chord Length (mm)	Bending Moment on the Front Spar	Bending Moment on the Rear Spar	Moment of Inertia of the Front Spar	Moment of Inertia of the Rear Spar	Torque	Shear Flow	Shear Force on the Front Spar	Shear Force on the Rear Spar
1	277.77	0	0	0	0	0	0	0	0
2	288.99	664.61	938.27	32.16	15.13	530.49	0.11	14.36	16.65
3	300.22	2680.40	3784.09	129.69	61.03	1124.01	0.23	29.29	33.97
4	311.44	6099.83	8611.53	295.15	138.89	1783.00	0.35	44.79	51.94
5	322.66	10249.22	14469.49	495.93	233.38	2509.92	0.47	60.86	70.57
6	333.88	16628.93	23476.14	804.62	378.65	3307.22	0.60	77.50	89.87
7	345.11	24573.93	34692.61	1189.06	559.56	4177.33	0.74	94.70	109.82
8	356.33	34132.31	48186.79	1651.56	777.20	5122.70	0.88	112.48	130.43
9	367.55	45356.48	64032.68	2194.66	1032.78	6145.79	1.02	130.82	151.70
10	378.77	58298.87	82304.29	2820.91	1327.49	7249.05	1.17	149.74	173.64
11	390	73011.87	103075.59	3532.83	1662.51	8434.91	1.32	169.22	196.23

The final mass of the spars was deduced as 199.89 grams from the optimized thickness, higher than that from initial thickness by 80 grams. A CAD model was then designed on SolidWorks according to the dimensions obtained from the code.

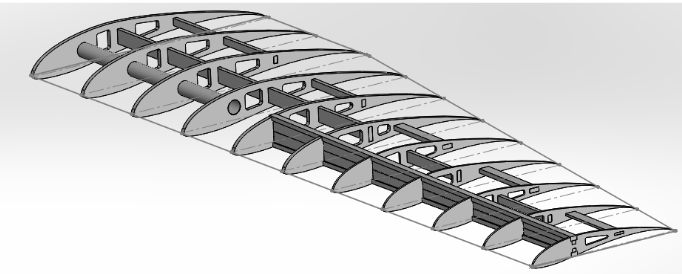


Figure 9: CAD Model of Wing.

ANALYSIS

The wing, designed in SolidWorks was analyzed on ANSYS Structural. Material properties of Aluminium 2024, Birchwood and Balsa wood were inserted from the library. The wing was then transformed into a mesh of finite elements. Simulating an actual scenario, the root rib was secured by applying boundary conditions. Further, load, calculated using the elliptical lift distribution curve was applied to the center of pressure of individual ribs. Finally, self-weight was enforced by inputting the acceleration due to gravity in the vertically downward direction.

Table 4: Force Applied on Ribs

Rib	Force (in N)
1	4.026
2	8.053
3	12.424
4	13.92
5	15.876
6	16.452
7	16.797
8	17.142
9	17.142
10	17.026
11	16.452

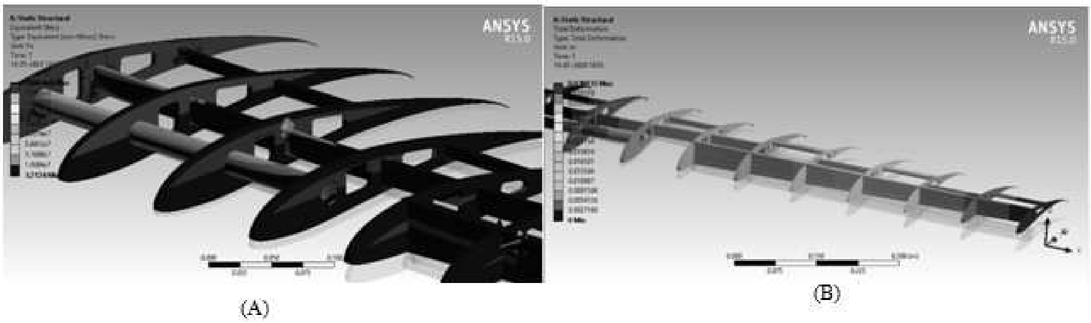


Figure 10: (A) Von-Mises Stress (B) Total Deformation Contours.

Table 5: Result of Structural Analysis

Paramter	Value
Total Deformation	3.8 cm
Maximum principal stress	197 MPa
Equivalent elastic strain	0.0128
Maximum shear stress	97 MPa
Equivalent (von-mises) stress	169 MPa
Yield strength of Aluminum	270 MPa
Safety factor	1.37

FABRICATION

The individual components of the wing were CNC router cut and were assembled over a 2-D drawing sheet. Areas bearing high load, such as the front spar, rear spar, root ribs were bonded using high strength epoxy, while others were secured using cyanoacrylate. The alignment of the wooden grains was kept parallel to the direction of the load to maximize strength. The servo motor box was installed and subsequently, the aileron was attached to the wing. The leading edge was machined to form an aerodynamic shape and finally, the wing was covered with monokote.

Figure 11: Assembled Structure.

Figure 12: Machining of Leading Edge.

RESULTS AND DISCUSSIONS

The paper determines an effective design methodology for the structural design, optimization and fabrication of a UAV wing. The complete fabrication was carried out in a span of 11 days and the final weight of the wing was recorded as 800 grams. A safety factor of 1.37 yielded after structural analysis validates the design and the objective of the investigation is accomplished. The designed wing, thus, can be concluded to be staunch, safe and efficient for lifting heavy payloads.

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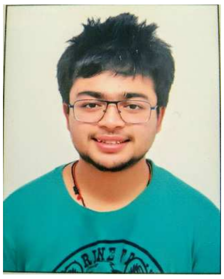
AUTHOR'S PROFILE



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1. Technical report for design and fabrication of regular and micro sized Unmanned Aerial Vehicle for Aero Design Challenge at SAE India Southern Section.
2. Technical report for design of an autonomous launch pad at TATA Pioneer's Makerthon.
3. White paper for design of Unmanned Aerial Vehicle for Mehar Baba Prize Competition organized by Indian Air Force.
4. Recently submitted a research paper titled "Numerical Study of Fracture Parameters for Slit Specimens for Al2124 and Micro Alloyed Steel" at ICAPIE – 2019, to be published in Lecture Notes in Mechanical Engineering.
5. Recently submitted a research paper titled "Shape-Changing Airfoil and Actuated Elevons For Micro-Aerial Vehicle: UniMorph" at ICMPC – 2020.

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Publications –

1. "The Design and Validation of Engine Intake Manifold using Physical Experiment and CFD" published in "International Journal of Automobile Engineering Research and Development" Paper ID: IJAuERDDEC20191

2. "Design and Development of Inertia Dynamometer for FSAE Application" published in "International Journal of Advance Research and Innovation" Paper ID: IJARI-ME-19-03-110

3. "Design and Optimization of Crankshaft for Four Cylinder 4-Stroke Spark Ignition Engine using Transient Structural Analysis" published in "International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) " Paper ID: IJMPERDOCT2019106

Rupanjali Kukal is pursuing her bachelors of technology in Mechanical Engineering with specialization in Automotive engineering from Delhi Technological University (formerly Delhi College of Engineering), conducting research in the field of structural and computational field. She has in depth theoretical and practical knowledge in solid mechanics, finite element analysis and structural designing.

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- Sanjay Kumar," Comparison of Deflection and slope of Cantilever Beam with Analytical and Finite Element Method for Different Loading Conditions" International Journal of Engineering Science and Innovative Technology (IJESIT), Volume 5, Issue 6, November 2016: ISSN: 2319-5967.
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  - Sanjay Kumar, Anoop Kumar Pandouria and Vikrant Tiwari “Design and fabrication of Three Point Bend Set up for Dynamic loading at 5th International Symposium on Fusion of Science &Technology(ISFT-2016) “for International Conference on Advance in Science and Engineering (ICASET-2016),held at New Delhi, India on 18-22 January, 2016.
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